AAS 99-336

SOLAR SAIL TRAJECTORIES FOR SOLAR-POLAR AND INTERSTELLAR PROBE MISSIONS[†]

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ABSTRACT

Solar Sail trajectories for two high energy Space Physics missions, Solar Polar and Interstellar Probe, are examined in this paper. An ideal, perfectly reflecting, flat sail together with optimal thrust steering is assumed in the trajectory synthesis. Parametric data is presented for both missions as a function of both sail characteristic acceleration and minimum solar distance.

The purpose of the Solar Polar mission is to place a payload into a short period, circular polar orbit about the Sun. The Interstellar Probe mission is to place the spacecraft on a heliocentric escape trajectory that will reach 100 to 1000 AU in 10 to 20 years in the direction of the solar apex. The above requirements dictate trajectories that are much more energetic than any that have been previously flown and appear most attractive using solar sails as the propulsion medium.

INTRODUCTION

During the past several years there has been renewed interest in the use of solar-sails for several proposed NASA high energy missions. Although a comprehensive set of solar-sail missions was investigated over 20 years ago[1,2] the maturity of solar sail technology at that time was not sufficient to enable these missions. Advances in both material technology and computer simulation capability over the past 20 years could do much to enable solar sails as a powerful propulsion option for future space missions.

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† The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California under contract with the National Aeronautics and Space Administration

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Because of the above advances, there has been renewed interest in the development of solar sail technology for NASA space missions. In addition, other agencies of the US government such as the National Oceanic and Atmospheric Agency (NOAA), the United States Air Force (USAF) and the Department of Energy (DOE) have expressed interest in this technology for monitoring and predicting the environment. A solar sail mission called Geostorm, under serious consideration by NOAA, would be stationed between the Earth and Sun to monitor and detect disturbances in the solar wind.[3]

In the NASA community itself there is currently interest in the use of solar sails for missions in addition to those to the planets and small bodies of the solar system. There are a number of missions included in the NASA Space Physics Division Sun-Earth Connection (SEC) Strategic Mission Roadmap[4] that are enabled by solar sails. These missions include a Solar Polar imaging mission and an Interstellar Probe mission, both relatively high energy missions. The Solar Polar imaging mission would place a spacecraft into a circular 0.48 AU or 1 AU solar orbit inclined 90 degrees. Solar Polar missions were examined briefly during a solar sail study 20 years ago. However, only in the past several years has a detailed systems study been made for such a mission. The Interstellar Probe mission would place a spacecraft on a heliocentric escape trajectory with departure excess speeds from the solar system of 10-50 AU per year. This mission would be designed to cross the heliopause in the direction of the solar apex and begin exploration of the local interstellar medium.

This paper presents the solar sail performance required for trajectories for the above two solar sail missions. It also extends the solar sail performance envelope for Solar Polar missions considered in prior solar sail studies and introduces the high energy solar sail trajectories required for the Interstellar Probe mission.

SOLAR SAIL DEFINITION

For this trajectory definition study, the solar sail is modeled as a perfectly reflecting flat surface. This assumption, while not quite achievable, does serve to define the upper limit for sail performance. A better approximation for the modeling of the sail, like that used in solar sail studies 20 years ago[5], requires a more detailed knowledge of the shape and reflective properties of the sail than that which is currently available. Since there is no fuel consumed during a solar sail mission, the performance index in the trajectory optimization is that of minimizing flight time for fixed values of sail characteristic acceleration.[†]

The trajectories generated for these two missions are characterized by departure from the Earth at zero excess speed (parabolic escape). These trajectories can then be used for either an escape from Earth orbit using a chemical injection stage or departure from Earth orbit using a solar sail spiral escape phase. Although performance can be improved by allowing

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† The sail characteristic acceleration is the force, which is the product of solar radiation pressure and sail area, applied to a perfectly reflecting sail oriented normal to the Sun line at a heliocentric distance of 1 AU, divided by the total spacecraft mass.

a positive escape energy, this energy can not be optimized without considering the actual physical properties of the sail and the launch vehicle performance. This would reduce the usefulness of these trajectories and examining each trajectory for a number of values of escape energy would be prohibitive. Since the departure energy from the orbit of the Earth is fixed, the effect of mass changes on sail acceleration due to changes in escape energy do not need to be considered and performance can be determined independent of the mass and size of the solar array by examining each mission parametrically in sail characteristic acceleration. Thus the performance presented for these two missions is applicable to a wide range of assumptions such as the areal density and size of the sail, payload mass and launch vehicle injection capability.

Optimization of the sail steering profile is based on a *Calculus of Variations* (COV) approach to trajectory optimization employed in previous sail trajectory studies.[6] In addition orbit parameters, not explicitly defined, are optimized by satisfying the *transversality conditions* that are inherent in the optimization process. A feature of the trajectories in this paper, not previously considered for solar sail trajectories, is that of constraining the minimum solar distance during the transfer trajectory. This constraint is necessary for Interstellar Probe missions since unconstrained optimal escape trajectories would otherwise pass very close to the Sun. Minimum solar distance constraints of 0.1 AU to 0.4 AU are considered for these solar sail Interstellar Probe missions and should be adequate to cover the range of minimum solar distances allowed for the various solar sail materials.

Conceptually the solar sail spacecraft can be divided into two mass components, a payload or net mass, M_N, and a sail mass, M_S, where the sail mass is the product of the sail area, S_0, and effective sail areal density, ρ, which includes the various supporting structures required by the sail. The characteristic sail acceleration a_C is then given by,

(1) $$a_C = \frac{P_a S_0}{M_N + S_0 \rho}$$

where Pa is the solar radiation pressure equal to approximately 9×10^{-6} N.m^{-2} for a perfectly reflecting flat surface at 1 AU. For a real solar sail, the actual acceleration imparted to the spacecraft at 1 AU and aligned normal to the Sun line will be less than the characteristic acceleration due to a less than 100% reflectivity and deviations of the sail from flatness. For the missions described in this paper, an ideal sail is assumed and the radial and circumferential sail accelerations are respectively,

(2) $$a_{radial} = \frac{a_C}{r^2} \cos^3 \alpha$$

(3) $$a_{circum} = \frac{a_C}{r^2} \sin\alpha \ \cos^2 \alpha$$

In the above equations r is the radial distance from the Sun in AU and α is the angle between the sail thrust vector or sail normal and the Sun line. The sail angle α is determined as part of the optimization process[6] and, for an ideal sail, lies between 0 and 90 degrees.

SOLAR POLAR MISSION

Science Objectives

A Solar Polar Imaging mission is an example of a science-enabled sail mission which has as its science objectives,[7]

- View the Sun from high latitudes.
- Discover the various features of the Solar corona.
- Image the global extent and dynamics of coronal mass ejections
- Link particle and field observations to images of Sun, corona and heliosphere at all latitudes.
- Determine magnetic field structures and convection patterns in the polar region of the Sun
- Follow the evolution of solar structures over a full solar rotation or more.

In order to provide frequent polar observations, a circular polar orbit with a 3:1 resonance with the Earth at a solar distance of 0.48 AU is desired. In addition to this orbit, orbits with a 5:1 resonance at a solar distance of 0.34 AU and a 1 AU orbit with a 1:1 resonance are also examined in this paper. Only the 1 AU and 0.48 AU circular polar orbits were considered in a previous JPL study[8]. However a polar orbit at 0.34 AU would allow more frequent passages over the poles of the Sun but would require a more advanced sail technology.

Trajectories

This mission is an example of a relatively near term solar sail mission. Trajectories with a range of sail characteristic accelerations of 0.2 to 1.6 mm/s^2 are examined and are applicable to solar sails with effective areal densities of 4-20 g/m^2. As a comparison the baseline solar sail Halley rendezvous mission[5] studied 20 years ago had a sail characteristic acceleration of 1.05 mm/s^2 and an effective sail areal density of 7-8 g/m^2.

In the 1996 JPL study[8] the trajectory for a Solar Polar imaging mission consisted of a single trajectory phase that had several close approaches to the Sun that were constrained at the final orbit distance of 0.48 AU. The flight time for the baseline trajectory in this study was nearly three years for a characteristic sail acceleration of 1 mm/s^2. This trajectory was not completely optimized in that the transfer time continually decreased as the trajectory transfer angle increased. Furthermore the increase in the transfer angle resulted in additional close approaches to the Sun. These additional close approaches had the effect of "tightening" the trajectory and, because of limitations of the trajectory optimization software, prevented optimization of the transfer angle. This limitation also precluded the examination of sail characteristic accelerations much below 0.97 mm/s^2 in this 1996 study.

In order to find trajectories with shorter flight times than that used in the previous study and also to examine performance at values of characteristic acceleration down to 0.2 mm/s^2, recourse was made to a two phase trajectory scenario that is likely very close to being optimal. In this scenario, the initial phase of the trajectory delivers the spacecraft to a circular orbit at the desired orbital distance and at an inclination of 15 degrees. This inclination was chosen since an inclination much above this would require that a closest approach distance constraint to the Sun be applied to the trajectory. Because the total transfer time is relatively insensitive to initial cranking orbit inclinations above10 degrees, a value of 15 degrees was arbitrarily chosen to avoid constraining the minimum distance.

The second phase of the trajectory consists of a *cranking* orbit where the remainder of the inclination gain is achieved. In this second trajectory phase the sail is aligned such that the sail thrust vector is normal to the spacecraft velocity vector. This alignment allows the sail to remain at a constant distance from the Sun. By reversing the sail direction twice per orbit at the time of maximum or minimum heliocentric latitude, a monotonic increase in inclination can be achieved with the line of nodes of the cranking orbit remaining relatively constant. An advantage of this scenario is that the cranking orbit can be calculated analytically without recourse to numerical integration. This cranking orbit was used 20 years ago in generating solar sail rendezvous trajectories to comet Halley.[5]

An example of this two phase approach for the generation of solar sail Solar Polar trajectories is shown in the two figures below. An ecliptic plane projection of the initial trajectory phase for a solar sail trajectory to a final radius of 0.48 AU and an inclination of 15 degrees is

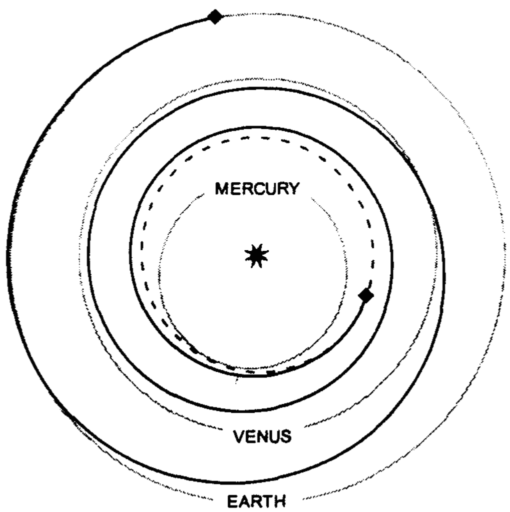

Figure 1 Earth to Cranking Orbit Phase

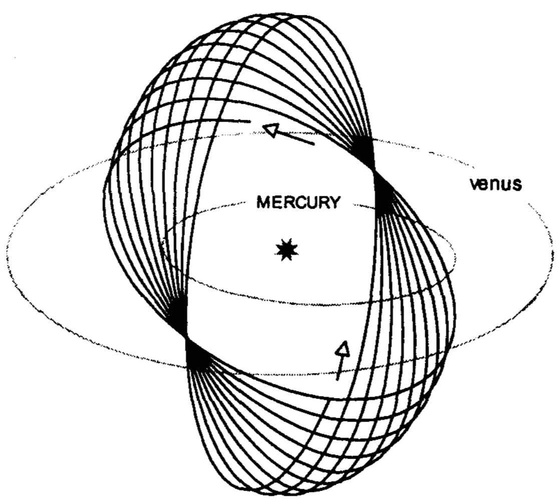

Figure 2 Cranking Orbit to 90 Degrees

shown in Figure 1 for a sail acceleration of 0.5 mm/s^2 A three dimensional view of the following cranking orbit is shown in Figure 2. Note that these two figures are not to the same scale. In Figure 1 the orbits of the Earth, Venus and Mercury are shown together with start of the cranking orbit shown by a dashed curve. Only the orbits of Venus and Mercury are shown in Figure 2 with the initial and final points on the cranking orbit indicated by the short arrows. The trajectory shown in Figure 2 was actually generated by numerical integration to check the analytic approximations.

The initial trajectory phase from the Earth to the cranking orbit, shown in Figure 1, had a transfer time of 578 days and a transfer angle 2.7 revolutions about the Sun. Another 1212 days were then spent in the cranking orbit which had a transfer angle of 9.6 revolutions. The total trajectory transfer time for these two trajectory phases was 1790 days or 4.9 years. The variation of the spacecraft orbit inclination and ascending node with time is shown in Figure 3 for the Solar Polar mission shown in Figures 1 and 2. The "wiggles" in the curves in Figure 3 occur because the rates of change of these two orbit parameters are variable during the cranking orbit. While the variation of inclination is proportional to the cosine of latitude, the variation of the ascending node with time, conversely, is proportional to the sine of latitude of the solar sail spacecraft. Since there is a thrust direction reversal at the maximum and minimum latitude, the effects on inclination are additive while the effects on ascending node cancel during a complete orbit phase such that the line of nodes remain relatively constant.

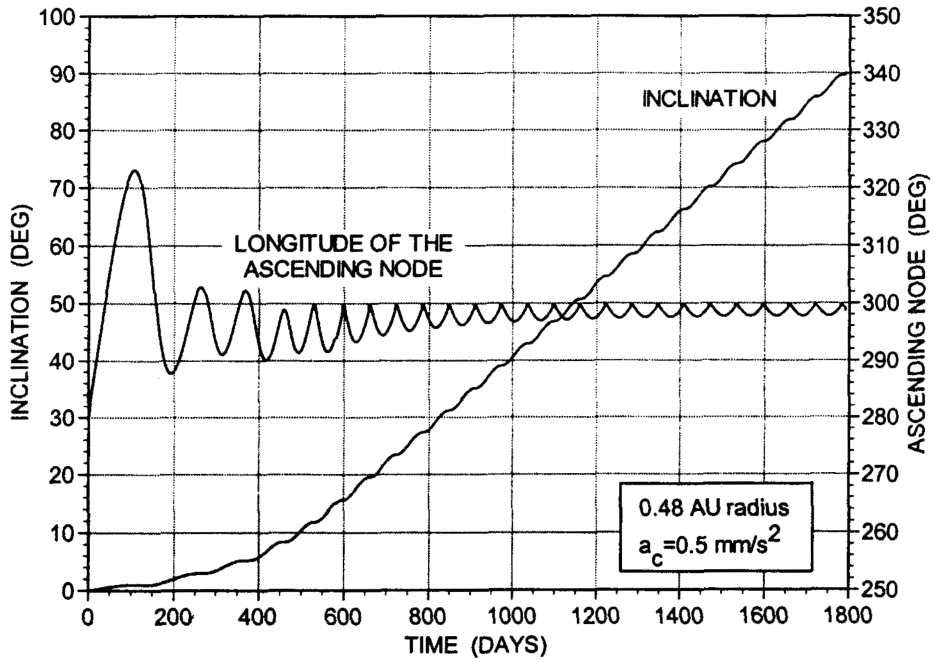

Figure 3 Variation of Inclination and Ascending Node in Cranking Orbit

In a solar sail trajectory there is always a positive radial component of thrust acceleration present. The effect of this radial acceleration in the cranking orbit is to behave like a reduction in the gravitational attraction of the Sun. As a consequence the orbital speed is less and the orbital period longer than that which would be expected at that radial distance from the Sun. Although this effect is small, it must be considered in calculating the cranking orbit trajectory. For example the orbit period for the cranking orbit in Figure 2 is 124.70 days compared with 121.75 days for an unperturbed solar orbit at the same radial distance.

Both the change in inclination over an orbit and the period of the cranking orbit are functions of the angle between the sail normal and the Sun line. In calculating the cranking orbits used in this study, the sail angle was optimized to maximize the averaged rate of change of inclination with time during an orbit. This optimized angle varies somewhat with sail characteristic acceleration, from slightly more than 35 degrees at a sail acceleration of 0.2 mm/s^2 to slightly less than 33.6 degrees at a sail acceleration of 1.6 mm/s^2. Because the gravitational acceleration and sail acceleration both vary as the inverse square of the solar distance, this optimized sail angle, for a fixed value of sail acceleration, is independent of the radial distance of the cranking orbit as is also the change in inclination over an orbit. The change in inclination and the orbit period, however, are both functions of the characteristic acceleration of the sail. The average time rate of change of inclination over an orbit is shown in Figure 4 as a function of the sail characteristic acceleration for the two values of the cranking orbit distance, 0.48 AU and 0.34 AU, that are used in this study.

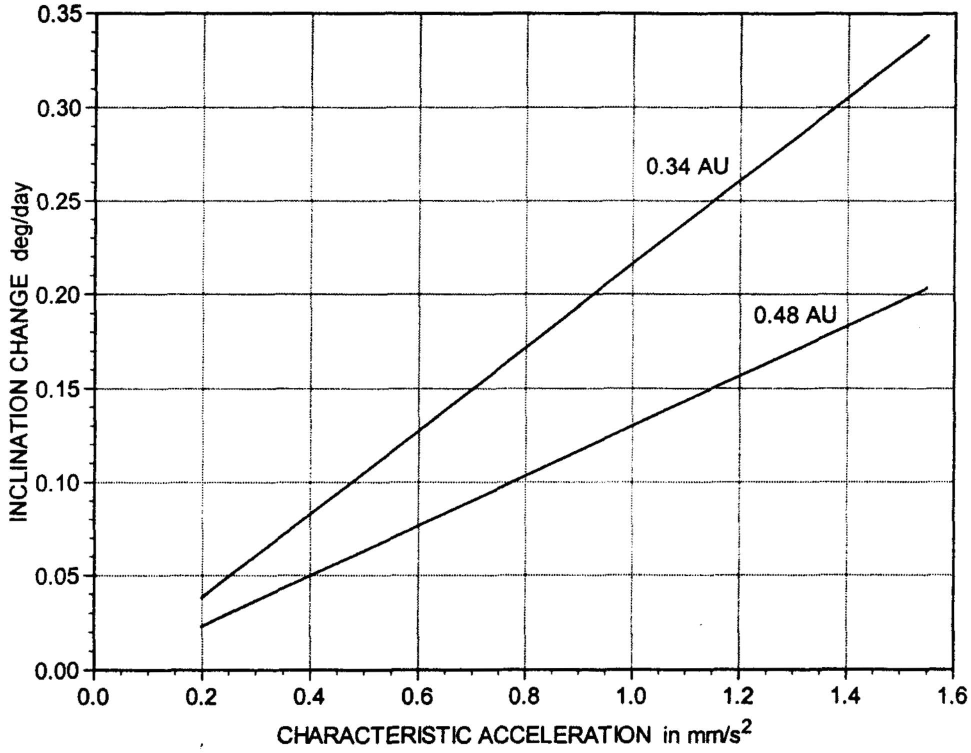

Figure 4 Average Rate of Change of Inclination in Cranking Orbit

An estimate of the time spent in the cranking orbit can be made by dividing the required inclination change, in the present study 75 degrees, by the average rate of change of inclination shown in Figure 4. The actual time spent in the cranking orbit will generally be different since an integral number of orbits are not usually required. This difference in time is neglected in the calculation of mission performance used in this paper. As an example the time spent in the cranking orbit for the trajectory shown in Figure 2 would be 16 days less were the time calculated using the average inclination change indicated in Figure 4.

Solar sail trajectories were calculated for each of the two solar distances being examined for characteristic accelerations varying from 0.2 mm/s^2 to 1.6 mm/s^2. These trajectories were targeted to a 15 degree inclination circular orbit at the appropriate solar distance and the line of nodes and the trajectory transfer angle were optimized such that the transfer time was minimized. Several mission scenarios were considered for each set of trajectories. For each set, the first scenario involved a final circular polar orbit about the Sun at the same distance as that of the cranking orbit. If a final polar orbit at 1 AU was desired rather than an orbit at the cranking orbit distance, however, a second scenario would include a third trajectory phase to place the spacecraft back out to a circular polar orbit at 1 AU. Although it would be possible to have a 1 AU cranking orbit for this latter mission, the time required would be long and it is more expeditious to go to a cranking orbit at a lower heliocentric distance and then return to 1 AU. This second scenario does not involve additional trajectory generation since the same trajectory can be used for the transfer from the cranking orbit to 1 AU as for the initial orbit from the Earth to the parking orbit. In the first mission scenario, the total mission time is the sum of the Earth to cranking orbit phase and the time in the cranking orbit to get to 90 degrees. In the second scenario, the total mission time is twice the sum of the Earth to cranking orbit phase and the time in the cranking orbit to get an additional 60 degrees, the

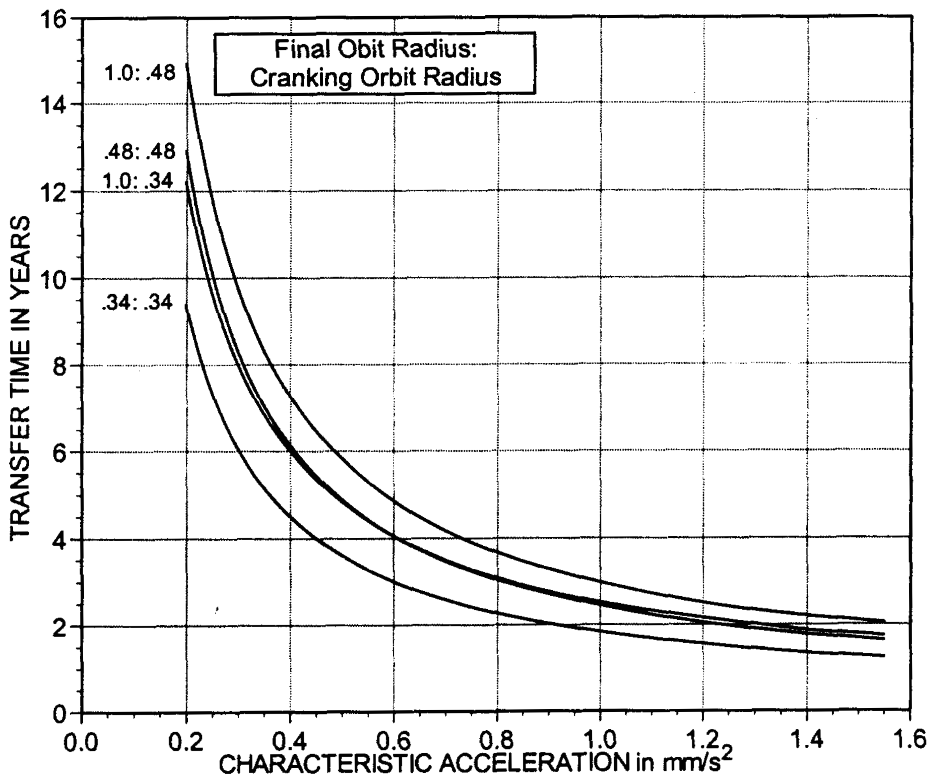

Figure 5 Total Transfer Time for Sail Solar Polar Missions

additional inclination being made up by the third phase from the cranking orbit to 1 AU. The results of these mission scenarios for the solar sail Solar Polar mission are summarized in Figure 5 which displays the total transfer time as a function of the sail characteristic acceleration.

It is apparent from Figure 5 that the characteristic acceleration should be at least 0.5 mm/s^2 or greater in order to get reasonably short flight times. In addition, there is not much to be gained by going to characteristic accelerations much above 1.5 mm/s^2 since the subsequent reduction in flight time appears minimal. In a real mission the phasing between the spacecraft in the polar orbit and the Earth must be considered. This phasing has been neglected in the results presented here, however the effect on total mission time will be small since this phasing is easily adjusted by changing the cranking orbit insertion point and initial inclination into the cranking orbit. Trade studies have shown that the total mission time is relatively insensitive to changes in initial cranking orbit inclination and optimized transfer angle.

INTERSTELLAR PROBE MISSION

Science Objectives

This mission, like the Solar Polar Imaging mission, is a key mission in the SEC Strategic Mission Roadmap. The Interstellar Probe mission presented in this paper can be viewed as a precursor mission to a future mission to reach the nearest star. This much more advanced mission would be on a trajectory that would cruise at an appreciable fraction of the speed of light. The precursor Interstellar Probe mission would be the first mission to reach the interface between the solar system and our galaxy and would travel to solar distances of 100 to 1000 AU in flight times of 10 to 20 years. This precursor mission would have as its science objectives,[4,7]

- Explore the nature of the interstellar medium and its implication for the origin and evolution of matter in the Galaxy
- Explore the structure of the heliosphere and interaction with the interstellar medium
- Explore the fundamental astrophysical processes occurring in the heliosphere and interstellar medium.

Trajectory

Although the Interstellar Probe trajectories are designed to escape from the solar system, they are optimized to minimize the time required to reach a particular solar distance. Sail accelerations are considered that should cover a range of sail technology levels from a near term, relatively low, technology level that would enable the solar sail spacecraft to reach 100 AU in 10-20 years to a far term, high technology level that would enable missions to 1000 AU in as short a time as 20 years. The Interstellar Probe trajectories presented in this paper all assume that the solar sail is jettisoned at 5 AU. The effectiveness of the sail in reducing flight time is minimal after the sail has reached a solar distance of 5 to 10 AU and it is assumed in the present study that the sail is jettisoned at this lesser distance to allow the acquisition of science data without possible interference from the sail.

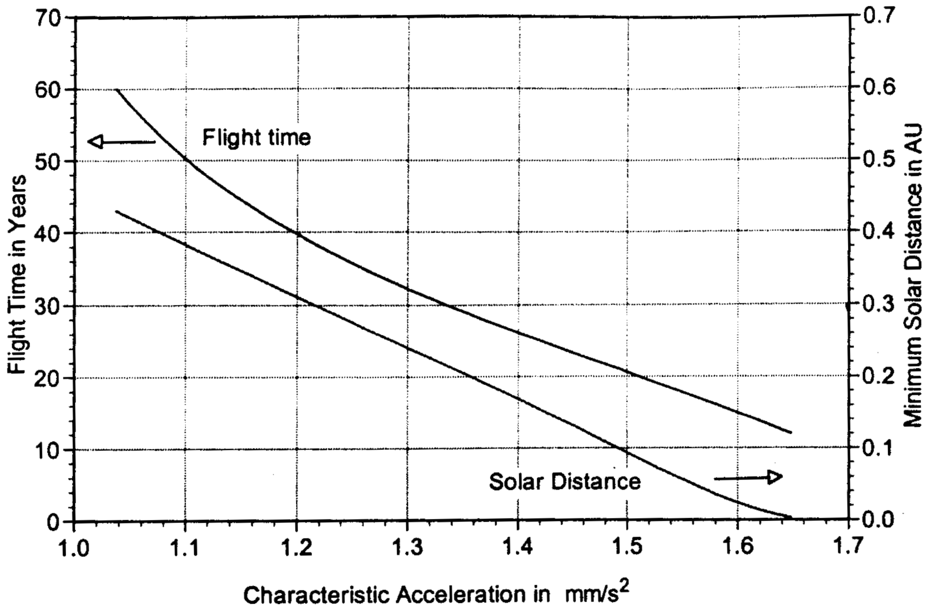

Figure 6 Unconstrained Flight Time and Minimum Distance to 250 AU

The flight time and minimum solar distance for a solar sail mission to 250 AU is shown in Figure 6 for trajectories without a constraint applied to the minimum solar distance. An observation of Figure 6 indicates that minimum solar distance is less than 0.1 AU for flight times less than about 22 years. An example taken from the above figure of the trajectory for a 20 year Interstellar Probe mission to 250 AU is shown in Figure 7 for a sail characteristic acceleration of 1.5 mm/s^2. Time tics are shown on this trajectory at 30 day intervals and only the initial phase of the trajectory to slightly past sail jettison is shown. The direction of the escape hyperbolic asymptote for all these Interstellar Probe trajectories is toward the solar apex which is the shortest distance to the heliopause or contact surface between the solar

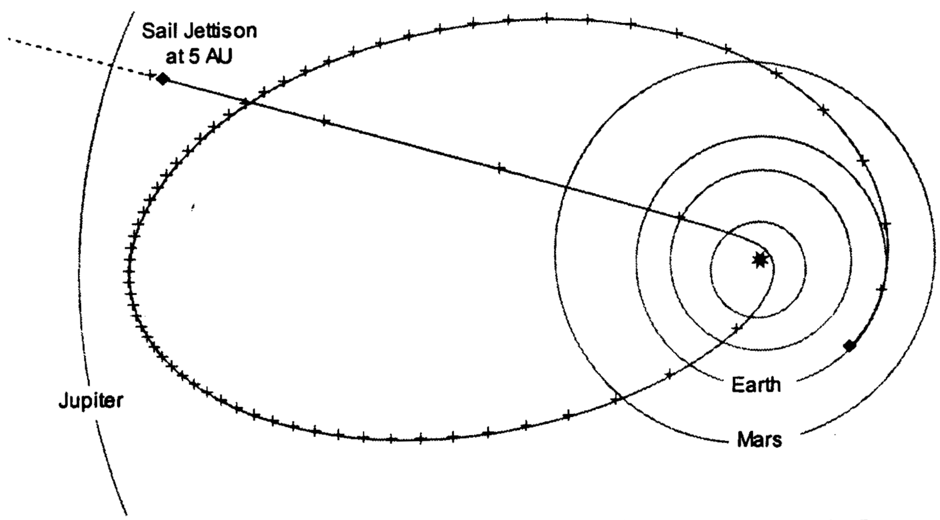

Figure 7 Unconstrained 20 Year Trajectory to 250 AU

system and interstellar space. The trajectory in the above example initially goes nearly to the orbit of Jupiter where much of the angular momentum is reduced allowing the sail spacecraft to pass close to the Sun where it is most efficient in adding energy to the trajectory. The minimum solar distance for this example is 0.086 AU, however, and is too close a distance to the Sun for anything except a very high technology solar sail.

If the assumption is made that the solar sail may go no closer than 0.2 AU to the Sun, then the trajectory would appear to be constrained to flight times of 30 years or greater. The characteristic acceleration for such a mission with a 30 year flight time is 1.34 mm/s^2 and is possibly achievable with a near term solar sail. Only by substantially increasing the sail characteristic acceleration above that shown in Figure 6 is it possible to travel to 250 AU in less than 30 years and yet get no closer to the Sun than 0.1 to 0.2 AU.

In order to examine Interstellar Probe missions for shorter flight times, it is necessary to include a constraint on minimum solar distance in the trajectory optimization. Estimates of sail acceleration and flight time from unconstrained solar distance trajectories such as in Figure 6 are used as starting conditions for the constrained solar distance sail trajectories. Solar distance constraints of 0.1 AU to 0.4 AU were examined as a function of sail characteristic acceleration for Interstellar Probe missions to 100 AU, 250 AU and 1000 AU. The range of constrained distances being considered should be adequate to cover both near term and far term sail technology levels.

Curves of minimum transfer time for an Interstellar Probe mission to 100 AU are shown in Figure 8 below. In this figure the unconstrained transfer time is indicated by the nearly vertical line at the left of the plot. This example of a precursor Interstellar Probe mission to

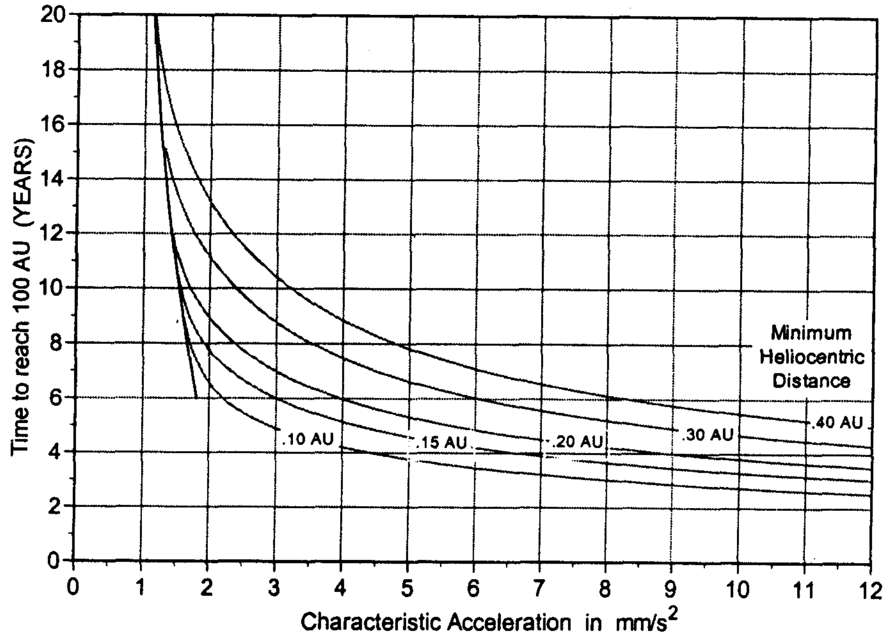

Figure 8 Minimum Time to Reach 100 AU

100 AU is appropriate for a near term sail mission where reasonably short flight times are possible without passing too close to the Sun. The data in Figure 8 and the corresponding data for the 250 and 1000 AU missions is useful since a broad range of sail technology levels can be examined.

If a sail technology is assumed that allows the solar sail to pass no closer that 0.3 AU to the Sun, then a sail characteristic acceleration of 2.4 mm/s^2 is required in order to reach 100 AU in 10 years. A plot of a solar sail trajectory for this 10 year mission to 100 AU is shown in Figure 9 where the trajectory after solar sail jettison is indicated by the dashed line. Since the sail acceleration is relatively low, the first part of the sail trajectory must go beyond the orbit of Mars before heading toward the Sun. This trajectory has a relatively low escape speed at sail jettison of 10.9 astronomical units per year (AU/Y). Time tics at 10 day intervals are shown on the trajectory in this figure and indicate that the sail takes around 165 days to go from the closest approach to the Sun to the orbit of Jupiter. In this figure the orbits of the inner planets and Jupiter are shown.

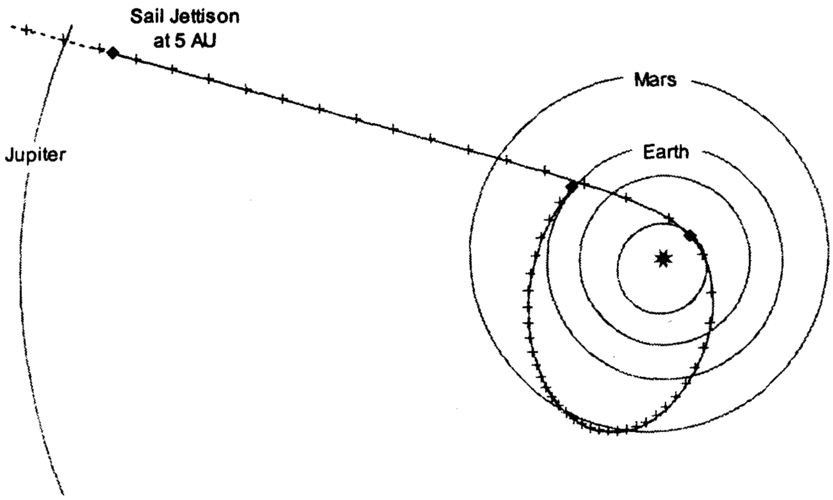

Figure 9 10 Year Solar Sail Trajectory to 100 AU

Curves of minimum flight time for a more distance 250 AU mission are shown in Figure 10. In this figure the nearly vertical line for an unconstrained trajectory is the same as the curve shown in Figure 6. An examination of the flight time in Figure 10 for a constrained distance of 0.2 AU shows that a sail characteristic acceleration of 2.1 mm/s^2 is required to reach 250 AU in 20 years and 8 mm/s^2 to reach the same distance in 10 years. This latter value of sail acceleration is significantly higher than the value shown in Figure 6 and indicates the cost in sail characteristic acceleration resulting from constraining the solar distance.

A plot of the projection of the trajectory on the ecliptic plane for a 10 year mission to 250 AU is shown in Figure11. A solar system hyperbolic escape speed of 26 AU/Y is attained at the time of sail jettison at 5 AU for this trajectory and it takes about 75 days to go from the closest approach to the Sun to the orbit of Jupiter. Since the sail acceleration is greater than that in the previous example of a mission to 100 AU, the initial phase of the trajectory need

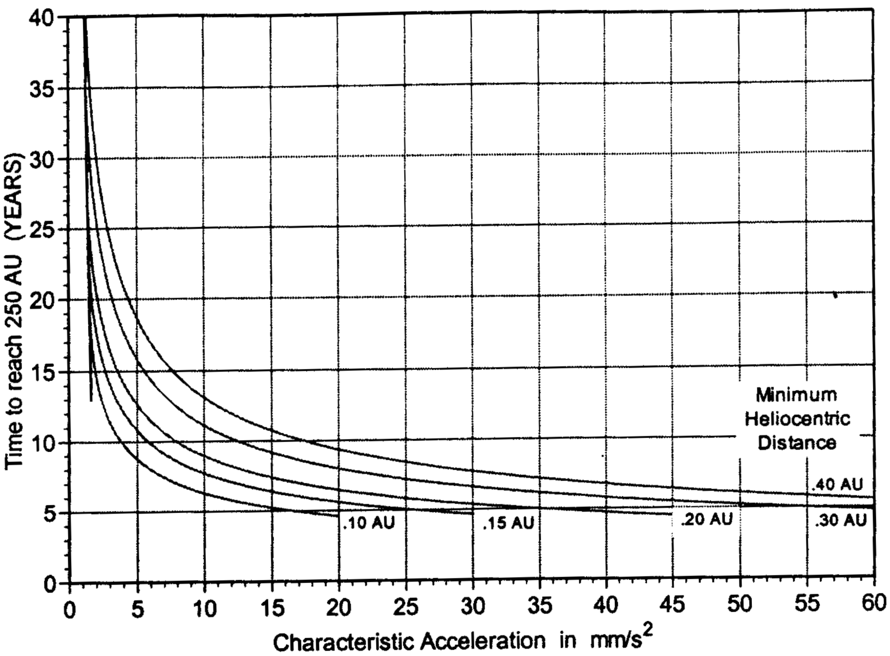

Figure 10 Minimum Time to Reach 250 AU

not go much beyond 1 AU before passing inside the orbit of the Earth and passing by the Sun at a closest approach distance of 0.2 AU. The trajectory shown in Figure 9 differs from the trajectory used for a solar system escape mission described by G. Vulpetti[9] because the sail orientation is optimized such that it is not necessary to reverse the angular momentum vector.

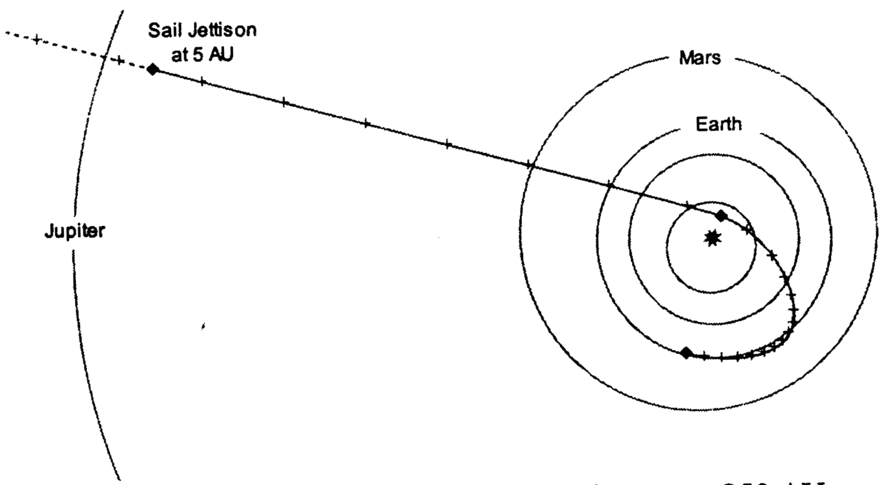

Figure 11 10 Year Solar Sail Trajectory to 250 AU

The final Interstellar Probe mission examined is one to 1000 AU. In order to achieve a short flight time for this last mission, both a close passage to the Sun and a large value of sail acceleration is necessary. Consequently this mission must be considered a far term solar sail mission. Performance similar to that shown in Figures 8 and 10 is presented for this 1000 AU mission in Figure 12. As indicated in this figure, it appears impractical to achieve mission times much less than 20 years. Even for a 20 year mission, very high sail accelerations are necessary even with close solar sail passages by the Sun.

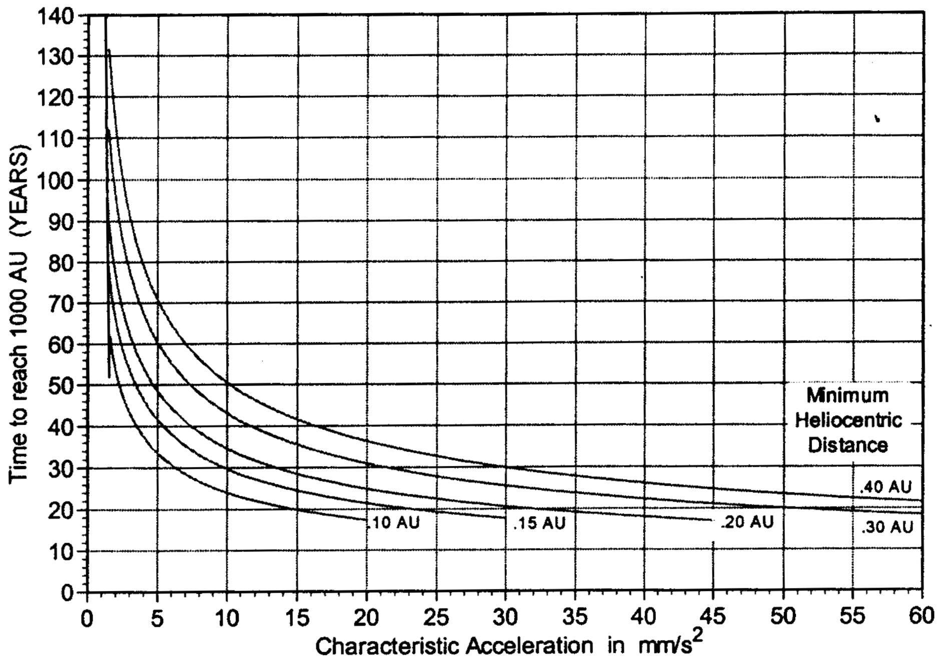

Figure 12 Minimum Time to Reach 1000 AU

An example of the trajectory for a 20 year sail mission to 1000 AU, constrained to a minimum solar distance of 0.1 AU, is shown in Figure 13. The sail characteristic acceleration for this mission is 15 mm/s^2 or 2½ times the gravity of the Sun, the sail departing from the solar system at an excess speed of nearly 51 AU/Y. This trajectory has a very short trajectory arc

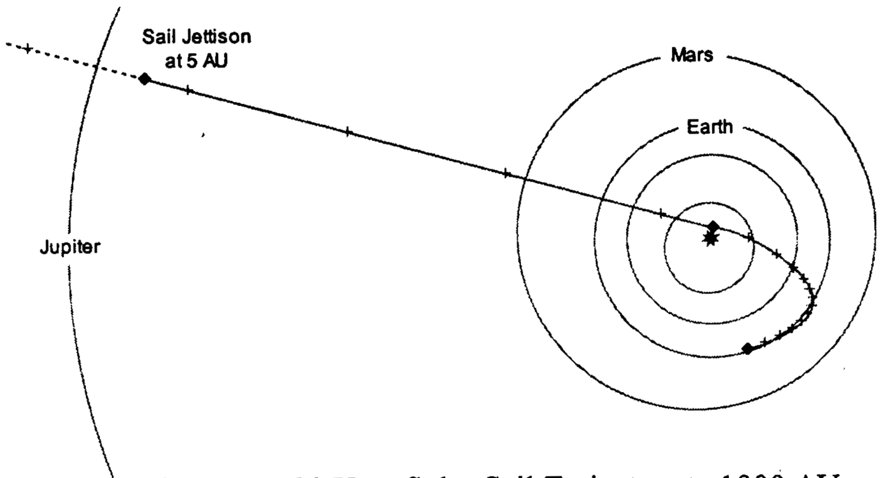

Figure 13 20 Year Solar Sail Trajectory to 1000 AU before plunging inside the orbit of the Earth and passing by the Sun. As seen in the plot of the trajectory, a transfer time of only 40 days is required to transport the solar sail spacecraft from the vicinity of the Sun to the orbit of Jupiter!

An important trajectory parameter for an Interstellar Probe mission, in addition to the minimum transfer time, is that of the solar system escape speed or hyperbolic excess speed. This escape speed is nearly invariant with the final solar distance for the same sail acceleration and constrained solar distance, the only significant difference in the escape speed

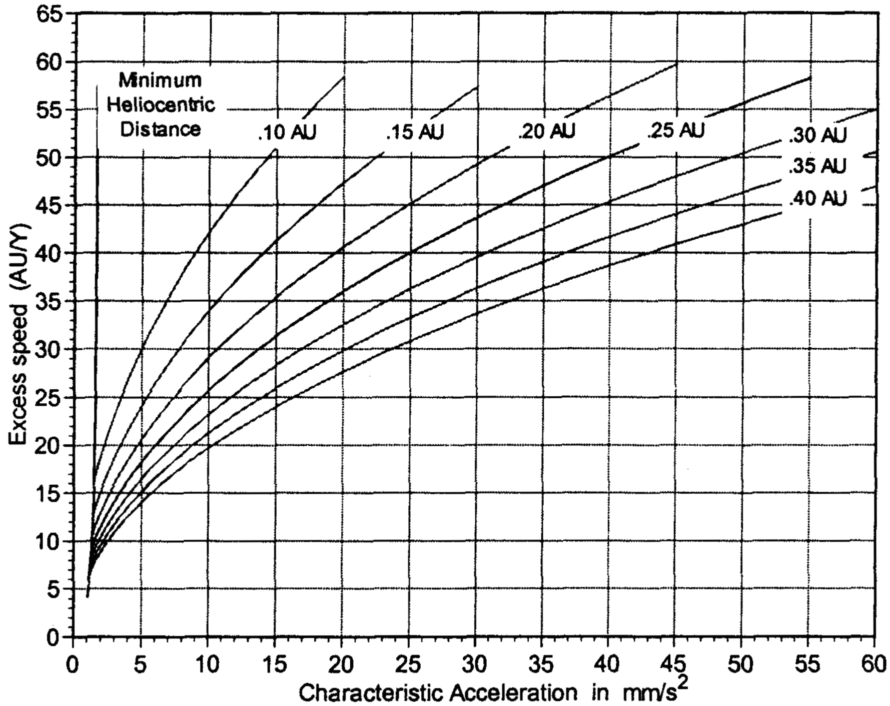

Figure 14 Hyperbolic Excess Speed

occurring for low values of sail acceleration. An example of this variation of excess speed as a function of sail acceleration and constrained distance is shown in Figure 14 for the sail mission to 250 AU.

SUMMARY

The material presented in this paper was generated to provide advanced technology mission planners with solar sail trajectory and performance trades for both the Solar Polar and precursor Interstellar Probe missions. A range of sail characteristic accelerations and constrained solar distances has been examined that will be sufficient to cover the expected gamut of sail technologies to be investigated in the near future. Both missions described in this paper are important parts of the Sun-Earth Connection Strategic Roadmap and the results presented here should prove invaluable for estimating future solar sail technology requirements for these Space Physics missions.

This paper has focused exclusively on the sail trajectories and avoided any examination connected with the mass, size, or physical properties of the sail. Using their own assumptions of effective sail loading, the reader can make estimates of payload mass and sail size from Equation 1 in this paper using the sail accelerations presented for the various missions. More accurate estimates of mission performance for these missions will be made when a better knowledge of the physical properties, such as reflectivity, of the solar sail are known.

ACKNOWLEDGMENTS

The material in this paper was developed over a one year period in support of an Advanced Technology Study at the Jet Propulsion Laboratory. The author wishes to acknowledge the support for this study by the Space Physics Advanced Missions Manager, Richard Wallace. Additional assistance and direction provided by Juan Ayon is also acknowledged.

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